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EFFECT OF AROMATICS AND SPARK ADVANCE ON THERMAL EFFICIENCY

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ADVANCE RESTRICTED REPORT

EFFECT OF AROMATICS AND SPARK ADVANCE ON THERMAL EFFICIENCY

By Mitchell Gilbert

SUMMARY

An analysis of experimental and theoretical data indicates that critical evaluation of fuel performance, especially economy, must be made in the engine. Specific factors, such as the aromaticity of a fuel and the degree of spark advance of the engine, may cause the thermal efficiency to vary at given fuel-air ratios. Thermodynamic analysis and consideration of combustion time indicate that this variation may be contrary to that expected from a knowledge of the change in heating value with change in fuel composition.

Data show that heating value is, from the aspect of fuel economy, not so important an aviation-fuel specification as believed.

The knock ratings of fuels are affected by spark advance. As spark advance must account for variations in burning time of fuels, it is to be expected that, over the range of fuel-air ratios, a constant spark advance must penalize some fuels more than others and the same fuel diversely, depending upon the magnitude of the spark advance. In instances in which the operating fuel-air ratio may be easily varied, advantages in fuel economy are obtainable without sacrificing knock rating by leaning simultaneously with retarding the spark.

INTRODUCTION

The results of a large number of tests of aviation-grade fuels in different engines have shown that one effect of the various components in the fuel is an increase or decrease in the engine thermal efficiency as determined by the indicated specific fuel consumption. In the fuel, additions of isopropyl ether and such aromatics as benzene, toluene, and xylene in various amounts and proportions

lower the indicated specific fuel consumption in rich
regions. In the combustion-air supply, a decrease in the
nitrogen-oxygen ratio improves the thermal efficiency.
The effect of water injection with the fuel is small under
conditions controlled by knock, but at constant manifold
pressure water may lower the thermal efficiency (refer-
ence 1).

These effects have been noticed, in general, for en-
gine tests run at constant spark advance. This spark
advance corresponds to the optimum value for the maximum-
power mixture, about 0.085 fuel-air ratio. The optimum
spark advance is defined as the spark advance which drops
the power from 1/2 to 1 percent below maximum. This
slight retarding of the spark allows greater inlet pres-
sures when knock data are obtained.

The data presented herein have been considered pri-
marily from trends that stood out from the errors and the
scatter of engine data. An apparatus as complex as an
engine obviously cannot be expected to give ideal experi-
mental data, but consistent trends may form a basis for
analysis. The ultimate wisdom of conducting engine tests
lies in the fact that theoretical considerations are often
contradicted or minimized in actual performance data.

Fuel-consumption data are considered as a function
of fuel-air ratio. A more fundamental choice than fuel-
air ratio would be the percent richness or percent lean-
ness based on the correct stoichiometric mixture for
different fuels. Since the actual engine must be con-
sidered, however, it must be realized that, in flight, the
flexibility of carburetor settings is limited and that,
outside these narrow limits, a given air flow brings about
the metering of a definite amount of fuel. This interre-
lation of fuel and air flow in the carburetor makes the
fuel-air ratio a more practical independent variable than
the percent richness or percent leanness.

Although the immediate problem is only that of the
effect of aromatics on thermal efficiency, oxygen, inert
gases, and water are mentioned as parameters affecting
thermal efficiency. Although the manner in which each
parameter influences thermal efficiency is complex, similar
trends indicate that the various parameters may similarly
influence the mass rate of combustion. The mass rate of
combustion is the resultant of factors such as tempera-
ture, pressure, chemical equilibrium, dissociation phenom-
ena, specific heats, thermal conductivities, heat losses,

and kinetic phenomena which govern reaction mechanisms,
energy distribution, ignition delay, surface effects, and
so forth. - As pointed out by Marvin (reference 2), the
thermal efficiency of an engine cycle will be determined
by the relation between the effective mass rate of combus-
tion and the piston position during the time interval of
unit mass combustion. As a consequence, the importance
of controlling the combustion—time—piston relation becomes
evident.

AROMATIC EFFECT

As previously stated, aromatic fuels tend to show
definite lowering of the indicated specific fuel consump-
tion for rich mixtures above 0.08 fuel—air ratio. At
mixtures leaner than the theoretically correct value, data
at Langley Memorial Aeronautical Laboratory (references 3
and 4) have not been conclusive, but some evidence indi-
cates that aromatic fuels at lean mixtures give higher in-
dicated specific fuel consumptions.

According to the relation

$$isfc = \frac{2545}{\eta H_c} \tag{1}$$

where

isfc   indicated specific fuel consumption, pounds per
       horsepower—hour

η thermal efficiency, percent indicated specific
       fuel consumption

H_c lower heating value of fuel, British thermal unit
       per pound·

2545   conversion factor, British thermal unit per horse-
       power—hour

fuels of low heating value, such as aromatic and other
fuels of decreasing hydrogen—carbon ratios, would give
higher rather than lower indicated specific fuel consump-
tions if their thermal efficiencies were about the same.

Calculations in reference 5 have shown that a 100-percent aromatic fuel such as benzene, considered from a percent rich-lean relation, would give only slightly different and somewhat lower thermal efficiencies than a paraffinic fuel; these calculations are based on a thermodynamic analysis of an engine cycle with corrections made for variations in specific heats of products and reactants for the kind and the extent of dissociation equilibriums. The data of figure 10 of reference 5 are replotted in figure 1 of the present paper with thermal efficiency as a function of fuel-air ratio and an entirely different picture results. The aromatic fuel is shown to give higher thermal efficiencies than the paraffinic fuel at fuel-air ratios in excess of 0.055.

In figure 1, the hydrogen-carbon ratio H/C has been introduced as a parameter to obtain a correlation for actual aromatics-paraffin mixtures. Intermediate curves are shown for 15- and 40-percent aromatic fuels; these curves were calculated on the assumption that, between pure benzene and pure octane, the thermal efficiencies of mixtures as a function of fuel-air ratio would produce a family of curves.

In order that the calculated values may be compared with observed engine data, the thermal efficiencies of figure 1 have been corrected to a compression ratio of 7.0 by data obtained from figure 8 of reference 5 and are shown in figure 2. Figure 8 of reference 5 gives thermal efficiencies calculated from thermodynamic analysis as a function of compression ratio and mixture ratio. The difference between the calculated and the observed curves in figure 2 represents the actual against the ideal engine cycle for a real fluid. About three-fifths the difference for similar fuels can be shown to represent heat losses (reference 6). The rest of the difference can be attributed to errors inherent in the thermodynamic analysis, such as lack of equilibrium, unknown dissociations, kinetic phenomena, and, most important, the error in the assumption that combustion is an adiabatic, constant-volume process. During combustion, the change in heat quantity ΔQ does not equal the change in internal energy ΔU but equals $\Delta U + \Delta W$, in which ΔW accounts for the work done on the moving piston. Hershey and Paton (reference 6) calculated the extent of ΔW and found it to vary from 1/2 percent at rich mixtures to $1\frac{1}{2}$ percent at lean mixtures. The engine heat losses vary similarly; hence, the wider spread between the curves in figure 2 at lean mixtures is somewhat accounted for.

Table I gives data for two fuels tested in the
Lycoming O-1230 cylinder:

TABLE I

Fuel	H_c	H/C
NACA 11	18,970	0.187
NACA 11 + 40 percent aromatics	18,362	.145

The aromatic blend consisted of 20 percent toluene, 15
percent xylene, and 5 percent benzene. Indicated specific
fuel consumption may be calculated by substituting in equa-
tion (1) the values for H_c given in table I and the
thermal efficiencies from the calculated curves in figure 2.
These calculated curves for the two fuels are superimposed
(fig. 3) over the actual data for indicated specific fuel
consumption obtained on the Lycoming cylinder. If the two
curves for the paraffinic fuels are assumed to be identi-
cal, the agreement between the solid curves represents the
deviation of actual engine data from the thermodynamic
analysis, after the heat losses and improper assumptions
have been eliminated. This agreement provides a further
check on the effect of aromatics. It must be emphasized
that the data chosen from tests at LMAL for comparison
with the calculated data of reference 5 are not only for
Lycoming O-1230 cylinder performance with 40-percent aro-
matic fuels but also for the Wright G-200 cylinder and are
typical whether tests were run at constant or at varying
inlet pressure. The agreement is good and further indi-
cates the possibility that aromatic fuels might give slight-
ly higher fuel consumptions than paraffinic fuels at lean
mixtures. From the mass of data, the extent of this in-
crease may be from 0 to 3 percent for fuel-air ratios
below 0.07. For rich mixtures from about 0.08 to 0.12,
the 40-percent aromatic blends give greater economy by 4
to 10 percent.

The significance of this increased economy in actual
flight can be considered not only from the effects on pay-
load but also from the aspect of carburetion. With carbu-
retor settings limited in flexibility, a change of fuel at

some flight stop from one of predominantly paraffinic
nature to, say, a 40-percent blend would result, for a
fixed setting of the cruise jet, in a fuel metering in-
crease of about 3 percent. This figure is based on the
square root of the density ratio of the two fuels because,
for turbulent flow, this relation controls jet metering.
An increase of 3 percent in fuel weight flow would increase
the fuel-air ratio correspondingly, but, for high-power
cruising, there would be no increase in indicated specific
fuel consumption.

This fact may be seen by examination of figure 3 at
the limits of high-power cruising, which might be between
fuel-air ratios of 0.07 and 0.10, depending on the fuel
knock rating and the service. An increase of 3 percent in
fuel-air ratio, from 0.070 to 0.072, will have no appreci-
able effect in the change from paraffinic to aromatic fuel.
An increase in fuel-air ratio from 0.10 to 0.103 in the
change from a paraffinic to an aromatic fuel will result
in a possible decrease in indicated specific fuel consump-
tion.

SPARK-ADVANCE EFFECTS

Because the theoretical cycle analysis is based on
instantaneous combustion and, in a real engine, finite
combustion time affects cycle efficiency, the results of
performance data must be examined from the aspect of spark
advance. The general practice of running with constant
spark advance set at the optimum position for maximum power
mixture introduces a retarding influence at fuel-air ratios
that give increased combustion times. Under such conditions,
fuel-air ratios richer and leaner than 0.08 will have their
pressure peaks delayed beyond the optimum position of 8° to
12° A.T.C. with resulting poorer than theoretical economy
but greater knock appreciation through low end-gas densi-
ties.

Figure 4 shows the effect of fuel-air ratio on opti-
mum spark advance for NACA fuel 10 with and without aro-
matics. The aromatic fuel is seen to burn relatively
faster than the paraffinic fuel at rich mixtures, giving
some indication of its slow rate of increase in fuel con-
sumption with fuel-air ratio at constant spark advance.
At lean mixtures, the relatively slower burning for the
aromatic than for the paraffinic fuel is an indication of

possible poorer economy at these mixtures. The lower part
of figure 4 gives the interesting corroboration of little
difference between the two fuels when optimum spark ad-
vance is plotted as a function of percent richness or
leanness.

Each fuel was run at constant manifold pressure with
the spark advance set at the optimum value for each fuel-
air ratio. The results of these tests are compared in
figure 5 with similar tests at constant spark advance
(21° for fuel 10, 22° for fuel 10 plus aromatics). When
the differences in combustion time are uncompensated for,
the aromatic fuel consumption differs in accordance with
the previous discussion. At optimum spark advance, it is
interesting that the specific fuel consumptions are the
same within the experimental error. The indicated specific
fuel consumptions are much lower, however, than those for
constant spark advance. This low specific fuel consump-
tion is explained on the basis of properly compensated
combustion time. The disappearance of differences in the
indicated specific fuel consumptions between the two fuels
can be explained by the greater increase in power for the
paraffinic than for the aromatic fuel in the change from a
retarded to an optimum spark. Of course, it follows that,
in rich mixtures, mixture ratio affects the paraffinic
fuel more detrimentally than the aromatic fuel. This fact
is seen in figure 4. Rich-mixture results given in refer-
ences 3 and 4 are more pronounced than those shown herein,
but the trend rather than the magnitude is considered the
important item in this discussion. The phenomenon, which
warrants further study in the engine, indicates the effects
of different combustion characteristics of fuels when spark
timing is not optimum. In reference 2, it was pointed out
that, under optimum conditions, widely varying mass rates
of combustion could give close agreement in cycle efficien-
cies, and the afore-mentioned data might be interpreted as
experimental corroboration.

The knock appreciation of a fuel with retarded spark
is indicated in figure 6. The increase in maximum per-
missible indicated mean effective pressure between fuel-
air ratios of 0.07 and 0.12 is considerably greater for a
constant spark advance set at the fastest burning mixture,
namely, 21° at about 0.08 fuel-air ratio, than for any
other value of spark advance. The curves for 30° spark
advance represent for fuel-air ratios between 0.05 and
0.13 a too far advanced spark and so reduce the permissi-
ble inlet pressure. At fuel-air ratios leaner than 0.05

and richer than 0.13, a spark advance of 30° tends to become optimum; whereas a spark advance of 21° is in effect an excessivly retarded spark. Under such conditions, therefore, the higher level of permissible inlet pressure obtained with a spark advance of 21° is not accompanied by a proportionate increase in power and the 30° spark advance enables the fuel to appreciate to a knock rating equal to that of the 21° spark advance. Presumably, at mixtures richer and leaner than those recorded within the inflammability range, the 30° knock curve would give better performance than the 21° knock curve. The 40°-spark-advance curve represents too great a spark advance for all fuel-air ratios tested and neither the permissible inlet pressure nor the power attains values as high as those for the 21° and the 30° spark advance.

Figure 6(c), which represents the fuel-consumption data, further indicates the importance of spark advance as a factor in thermal efficiency. Although, in the range of fuel-air ratios from 0.075 to 0.12, the permissible power level is much greater for a spark advance of 21° than for other values of spark advances, the 30° curve gives better fuel consumption than either the 21° or the 40° curve. The greatly undercompensating effect of 21° spark advance is shown by the fact that, at about 0.135 fuel-air ratio, the difference in indicated specific fuel consumption is about 10 percent.

Further tests should be run to investigate the effects of varying spark advance under all types of condition.

CONCLUSIONS

The results of representative tests at LMAL correlated with available theoretical data indicate the following conclusions:

1. The practical value of fuel-air ratio in the choice of flight conditions makes the comparison of fuels on a fuel-air-ratio basis more important than a comparison on a percent stoichiometric basis. Fuels of low heating value may tend to give higher indicated specific fuel consumptions when considered stoichiometrically, but aromatic fuels are seen to improve thermal efficiencies when considered as a function of fuel-air ratio. Fuels should be

compared on actual engine performance and such data will not contradict theoretical considerations if there is kept clearly in mind the differences between the independent variables used in the interpretation of the results.

2. Aromatics will increase fuel flow for given carburetor settings, but this increase will be occasioned by no increase and a possible decrease in specific fuel consumption as a result of increased thermal efficiencies.

3. The rich-mixture knock appreciation is to a considerable extent due to choice of spark advance. For cases in which requirements of service will not exceed a certain percent of the rating obtained with minimum spark advance, further spark advance will improve engine efficiency to some extent.

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    National Advisory Committee for Aeronautics,
       Langley Field, Va.

REFERENCES

1. Rothrock, Addison M., Krsek, Alois, Jr., and Jones, Anthony W.: Summary Report on the Induction of Water to the Inlet Air as a Means of Internal Cooling in Aircraft Engine Cylinders. NACA ARR, Aug. 1942.

2. Marvin, Charles F., Jr.: Combustion Time in the Engine Cylinder and Its Effect on Engine Performance. NACA Rep. No. 276, 1927.

3. Biermann, Arnold E., Corrington, Lester C., and Harries, Myron L.: Effect of Additions of Aromatics on the Knocking Characteristics of Several 100-Octane Fuels at Two Engine Speeds. NACA ARR, May 1942.

4. Krsek, Alois, Jr., and Jones, Anthony W.: Effect of an Aromatic Mixture Added to Two 100-Octane Fuels on Engine Temperature and Fuel Consumption. NACA ARR, June 1942.

5. Goodenough, George A., and Baker, John B.: A Thermo-
      dynamic Analysis of Internal-Combustion Engine
      Cycles. Eng. Exp. Sta. Bull. No. 160, Univ. Ill.,
      Jan. 1927.

6. Hershey, Albert E., and Paton, Robert F.: Flame
      Temperatures in an Internal Combustion Engine
      Measured by Spectral Line Reversal. Eng. Exp. Sta.
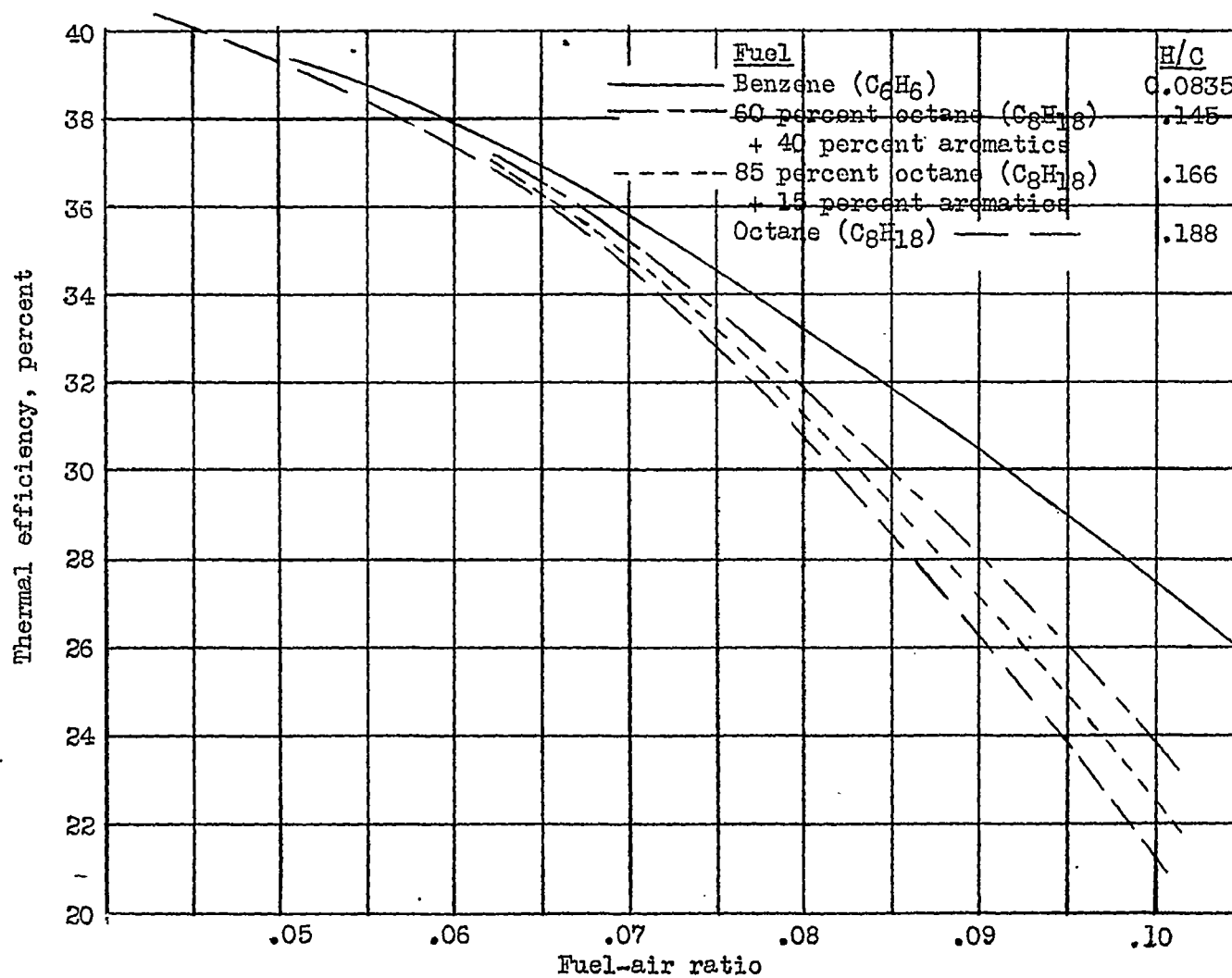   Bull. No. 262, Univ. Ill., Oct. 1933.

Figure 1.— Effect of fuel-air ratio on thermal efficiency for different hydrogen-carbon ratios. Compression ratio, 5.0. (Data from fig. 10 of reference 5.)

Fig. 1
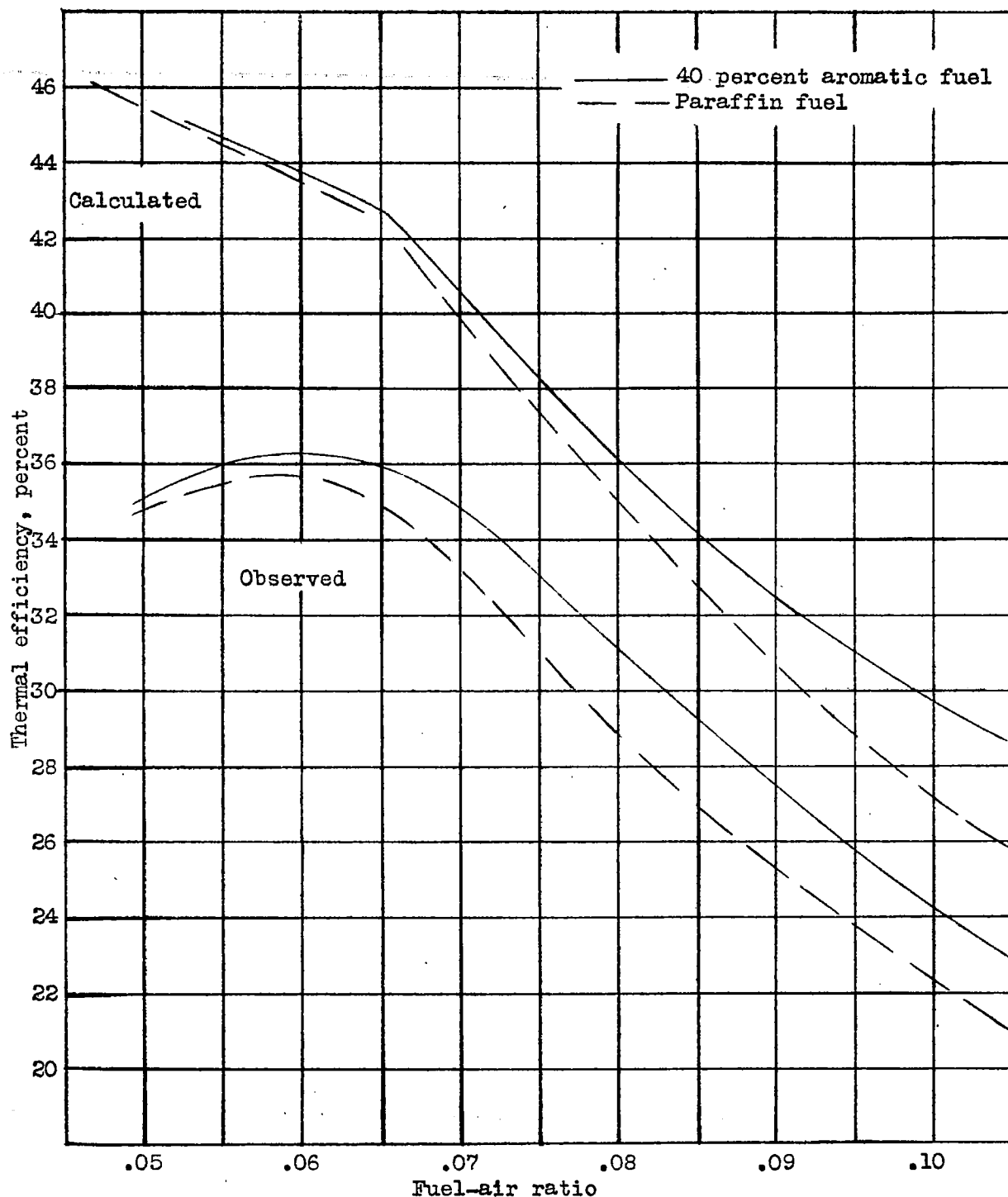
Figure 2.- Comparison between calculated and observed data on thermal
          efficiencies for similar fuels. Compression ratio, 7.0.
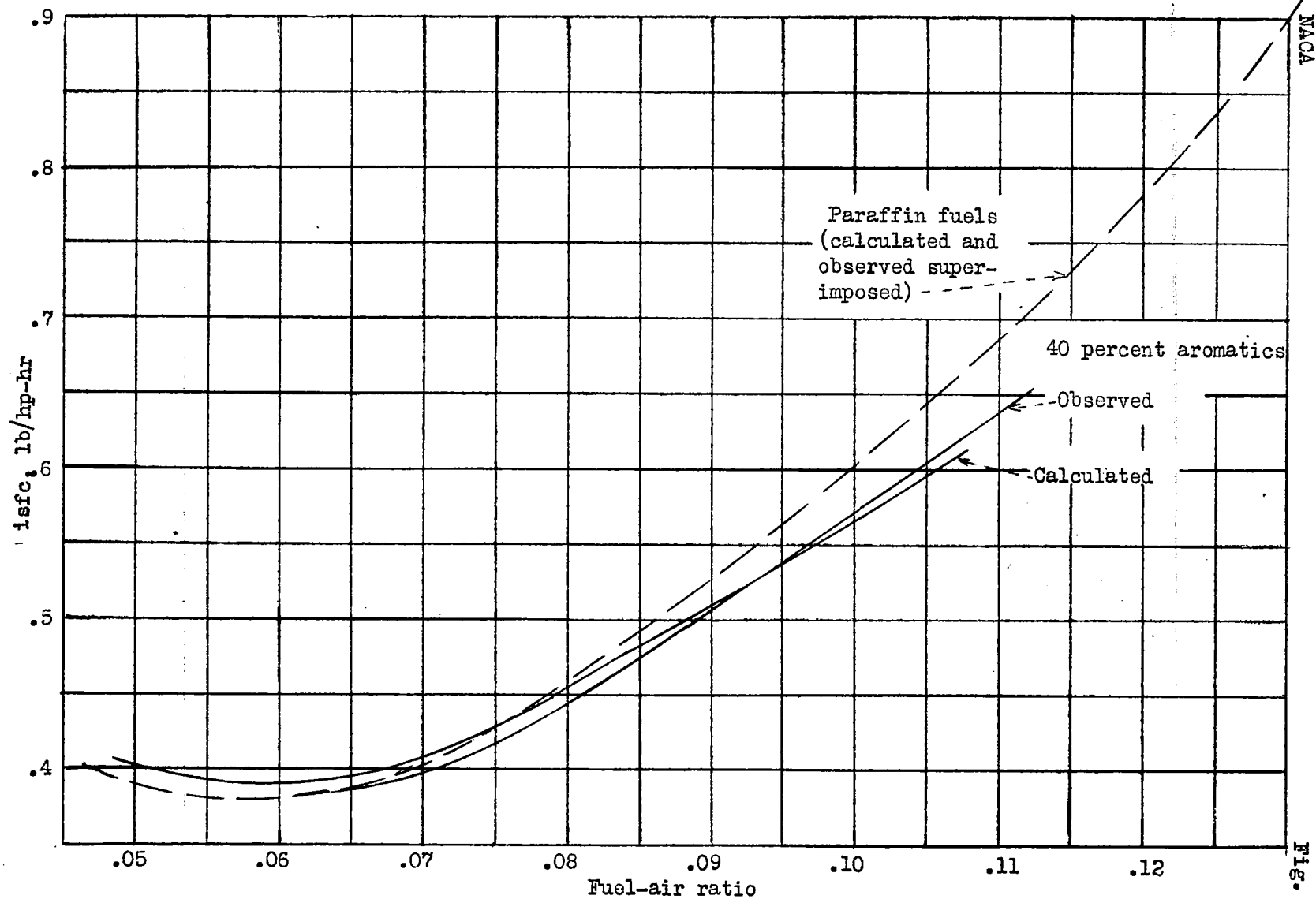   (Calculated data, reference 5; observed data, reference 1.)

Figure 3.– Comparison of calculated and observed data on effects of aromatics on indicated specific fuel consumption. Compression ratio, 7.0. (Calculated data, reference 5; observed data, reference 1.)
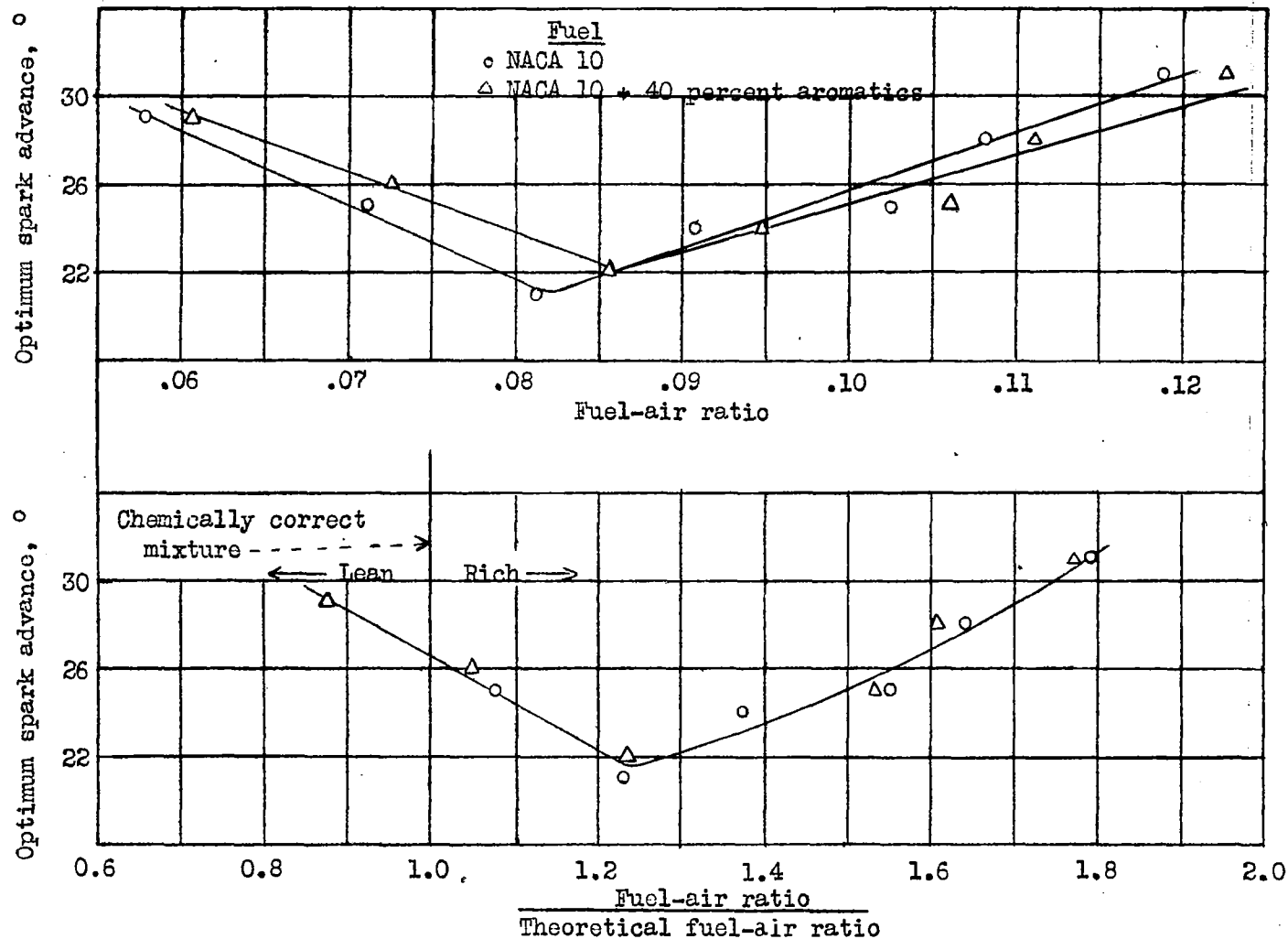
Figure 4.— Effect of mixture ratio on optimum spark advance for fuel 10 with and without aromatics. Lycoming O-1230 cylinder; engine speed, 2000 rpm; coolant inlet temperature, 250°F; compression ratio, 7.0; inlet air temperature, 250°F; inlet pressure, 33 inches Hg absolute.
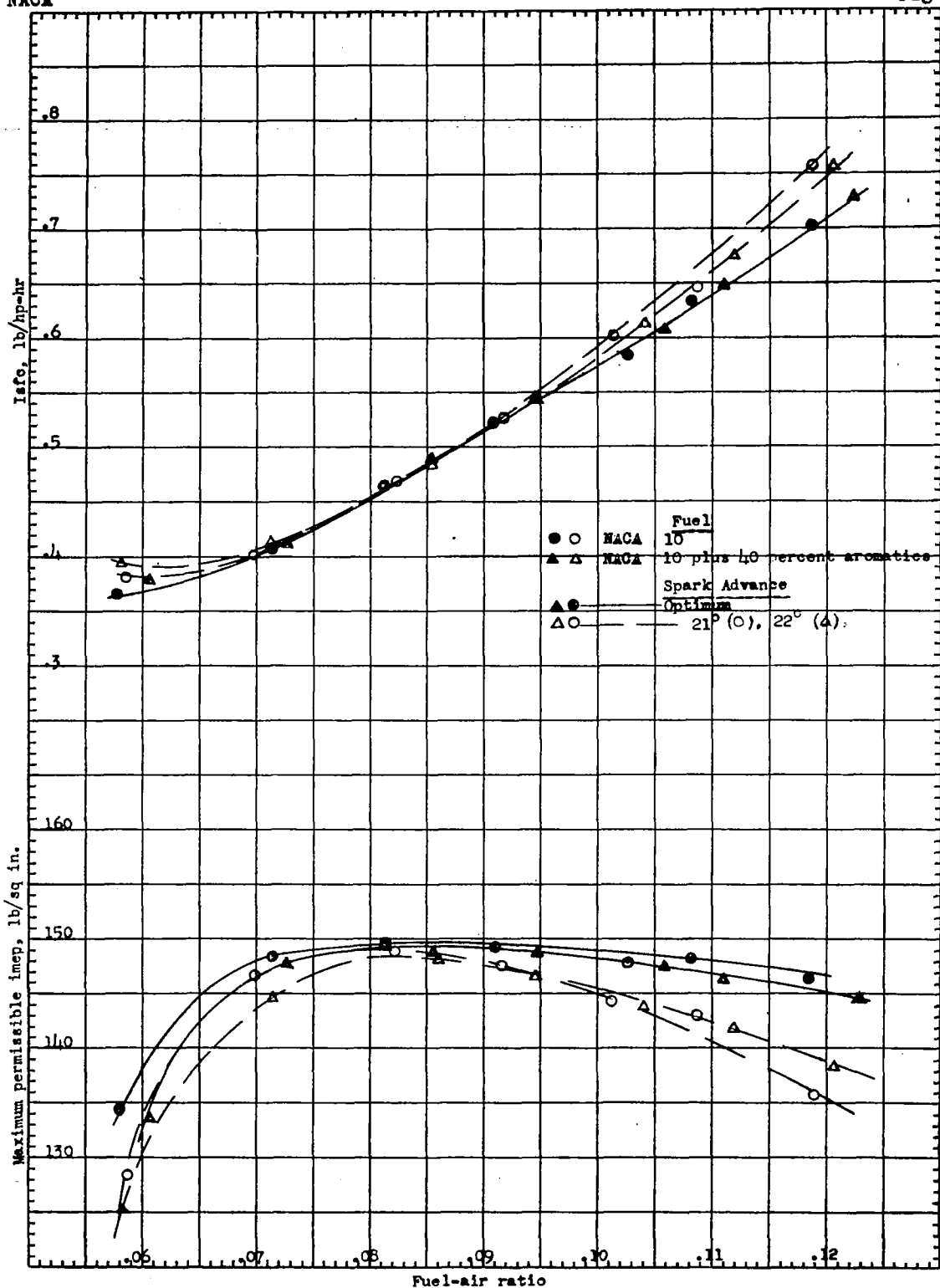
Fig. 4

Figure 5 .- Effect of constant and variable(optimum) spark advance on performance of fuel 10
    with and without aromatics. Lycoming O-1230 cylinder, engine speed, 2000 rpm; coolant inlet
    temperature, 250°F; compression ratio, 7.0; inlet air temperature, 250°F; inlet pressure, 33.0
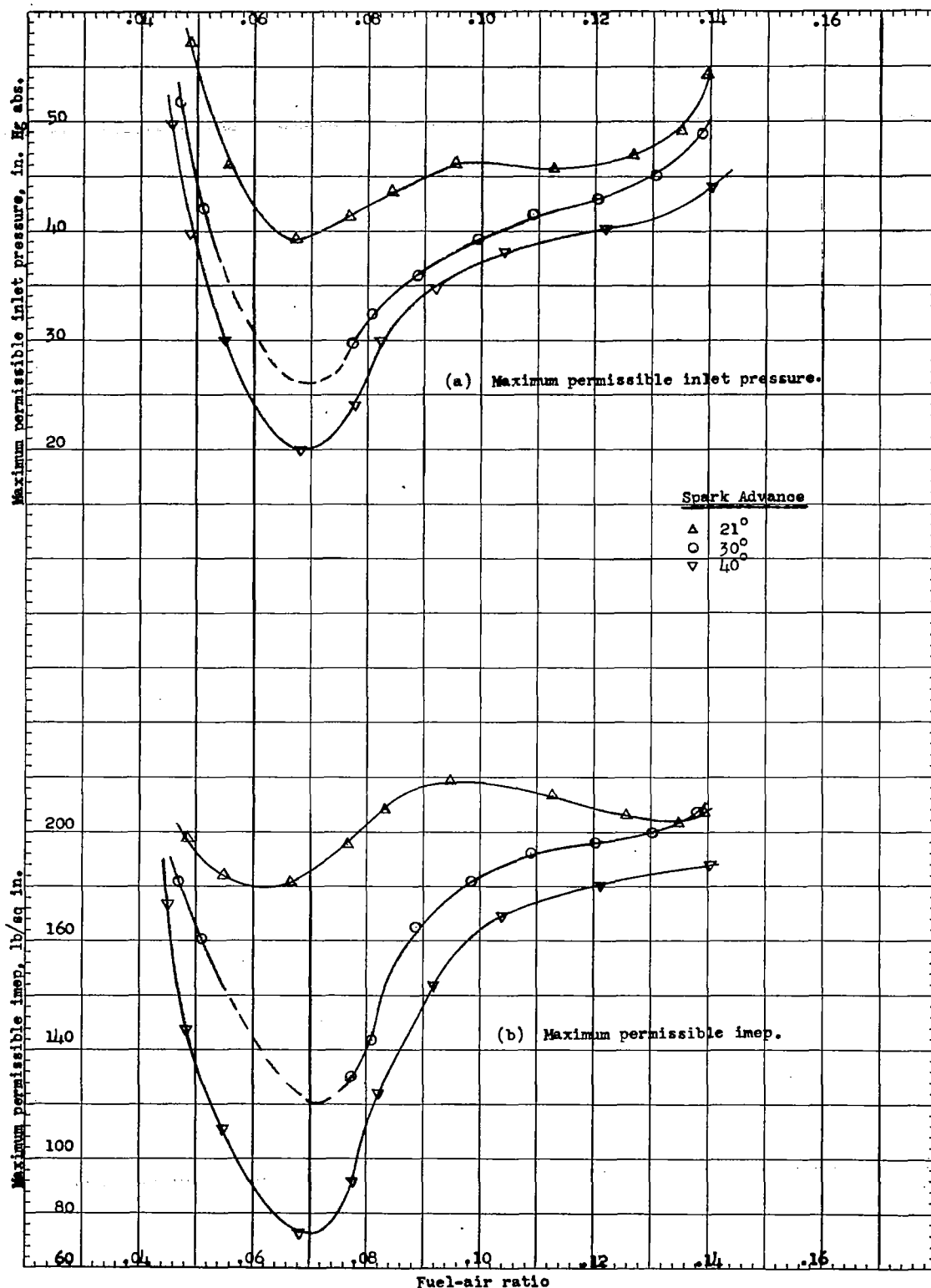   inches mercury absolute.

Figure 6. – Effect of varying spark advance on performance of fuel 10. Lycoming O-1230 cylinder; engine speed, 2000 rpm; coolant inlet temperature, 250° F; compression ratio, 7.0; inlet-air temperature, 250° F.
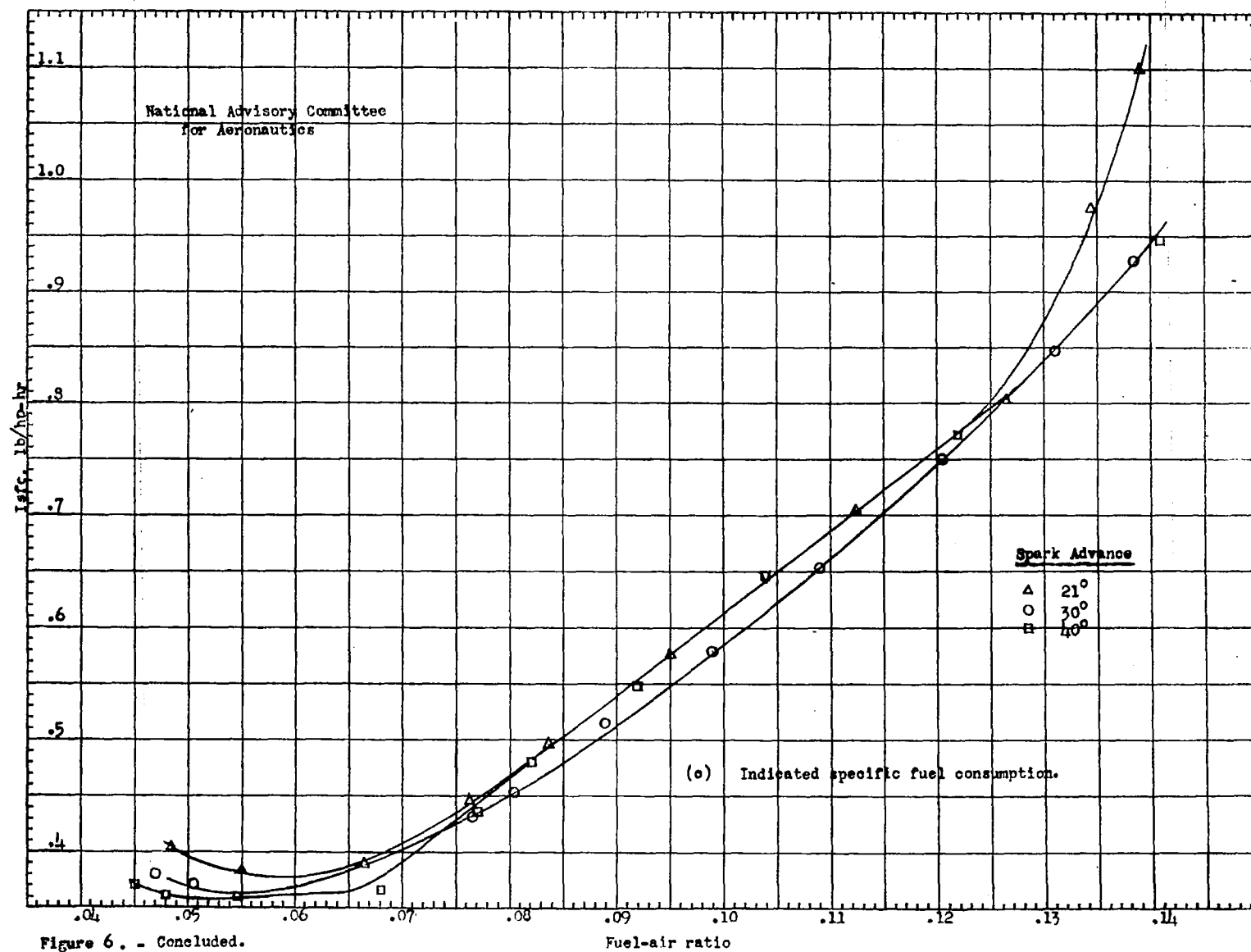
Figure 6 . - Concluded.